25PY101: Engineering Physics
Module 1 – Unit 1

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Assignment 1: Extrinsic semiconductors

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1 Extrinsic semiconductor

Reference: Section 4.3.2 – The n_0p_0 product [Neamen].
An intrinsic semiconductor doped with donor dopants results in n-type semiconductor. Let the majority carrier concentration be denoted by n_0 (n for negative) and minority carrier concentration be denoted by p_0 (p for positive).
The product of n_0 and p_0 is related to the carrier concentration of intrinsic semiconductor n_i by

$$n_0p_0 = n_i^2$$

This equation is called the $\mathbf{n_0p_0}$ **product** [1] equation and is one of the fundamental principles of semiconductors in thermal equilibrium.
If the donor concentration N_d is very high than n_i,

$$N_d \gg n_i,$$

then

$$n_0 \simeq N_d.$$

Similarly, for p-type semiconductor, if the acceptor concentration N_a is very high than n_i,

$$N_a \gg n_i,$$

then

$$p_0 \simeq N_d.$$

1.1 n-type semiconductor

Problem: For n-type Si, if $N_d = 10^{16}\,\mathrm{cm}^{-3}$ and $n_i = 1.5 \times 10^{10}\,\mathrm{cm}^{-3}$ at $300\,\mathrm{K}$ [2],

[1] We will derive this equation in the next unit.

[2] At room temperature, we can assume dopants undergo complete ionization in Si. The reason is ionization energy of dopants (like P, Al) in Si is of the order of $10\,\mathrm{me\,V}$ whereas thermal energy at room temperature is of the order of $26\,\mathrm{me\,V}$.

1. Which is the majority carrier?
2. Which is the minority carrier?
3. What is the majority carrier concentration?
4. What is the minority carrier concentration?
5. What is the ratio of minority to majority carrier concentration?

calculate the minority carrier concentration.

1.2 p-type semiconductor

Problem: For p-type Si, if $N_a = 5 \times 10^{15}\,\mathrm{cm}^{-3}$. Repeat the steps of previous problem.

2 Compensated semiconductor

Reference: Section 4.3.2 – Equilibrium Electron and Hole Concentrations [Neamen]. Consider an extrinsic semiconductor that contains both donor and acceptor impurities in the same region. Such a semiconductor is called a **compensated** semiconductor. Let the donor dopant concentration be N_d and acceptor dopant concentration be N_a.
An n-type compensated semiconductor occurs when

$$N_d > N_a,$$

and a p-type compensated semiconductor occurs when

$$N_a > N_d.$$

A **completely** compensated semiconductor occurs when

$$N_a = N_d.$$

Consider an n-type compensated semiconductor. If we assume complete ionization of dopants, then the equilibrium electron concentration n_0 is given by

$$n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

where n_i is the electron concentration of the intrinsic semiconductor.
Similarly, for p-type compensated semiconductor, if we assume complete ionization of dopants, then the equilibrium hole concentration p_0 is given by

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

2.1 n-type compensated semiconductor

Problem: For n-type compensated Si, $N_d = 5 \times 10^{15}\,\mathrm{cm}^{-3}$ and $N_a = 2 \times 10^{15}\,\mathrm{cm}^{-3}$. Calculate n_0 and p_0 at 300 K.

2.2 p-type compensated semiconductor

Problem: For p-type compensated Si, $N_a = 10^{16}\,\text{cm}^{-3}$ and $N_d = 3\times10^{15}\,\text{cm}^{-3}$. Calculate n_0 and p_0 at 300 K.

2.3 Fully compensated semiconductor

Problem: For fully compensated Si, $N_a = 10^{15}\,\text{cm}^{-3}$ and $N_d = 5\times10^{15}\,\text{cm}^{-3}$. Calculate n_0 and p_0 at 300 K.

3 Amphoteric dopants

Reference: Problem 4.62 [Neamen]
Si is an elemental semiconductor whereas GaAs is a compound semiconductor. Group IV elements such as Si can act as impurity atoms/dopants in GaAs.
Statement 1: If Si replaces Ga atom, the Si dopant will act as a donor.
Statement 2: If Si replaces As atom, the Si dopant will act as an acceptor.
Such dopants that can act as both donors and acceptors are called amphoteric dopants [3] and the extrinsic semiconductor will be a compensated semiconductor.
Problem: GaAs is doped with Si with concentration of $7\times10^{15}\,\text{cm}^{-3}$. Assume complete ionization of dopants at 300 K [4]. It is observed that 5% of Si atoms replace Ga whereas 95% of Si replace As. The intrinsic carrier concentration in GaAs is $1.8\times10^{6}\,\text{cm}^{-3}$.

1. Prove statements 1 and 2.
2. Determine N_d, N_a.
3. Is semiconductor n-type or p-type?
4. Calculate the majority and minority carrier concentration.

4 Mobility

Reference: Section 5.1 – Carrier drift [Neamen].

	Si	GaAs
μ_n ($\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$)	1350	480
μ_p ($\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$)	8500	400

Table 1: Mobility of carriers in Si and GaAs at 300 K.

Problem:

1. Discuss how the mobility of carriers depends on temperature.
2. Discuss how the mobility of carriers depends on doping concentration.

[3] Amphoteric is related amphibious which means "both". Frogs are amphibious animals.
[4] The ionization energy of dopants in GaAs is of the order of 1 meV whereas thermal energy at room temperature is of the order of 26 meV.

5 Conductivity

The conductivity σ of semiconductor is given by

$$\sigma = n_0 e \mu_n + p_0 e \mu_p.$$

Problem: Calculate the conductivities for all the previous problems.

End of Assignment